Microphonics and Active Compensation

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Acknowledgements

- Cryogenics: Ben Hansen, Renzhuo Wang, Michael White
- Tuner and ARC Group: Jeremiah Holzbauer, Yuriy Pischalnikov, Warren Schappert
- Cavity and CM Design: Joshua Kaluzny, Tom Petersen
- LLRF: Brian Chase, Larry Doolittle, Carlos Serrano, LCLS-II Collaboration, et al.
- Project Operations: Elvin Harms
- JLab: Tom Powers

Outline

- Introduction
- Definition (Microphonics/LFD)
- Effects
- Facility
- Diagnosis
- Mitigation
  - Passive
  - Active
- Auxiliary Systems Considerations

Introduction

- Superconducting cavities have extremely high Q values, which leads to minor physical variations able to cause singificant RF differences
- On higher frequency cavities, such as the 3.9 GHz cavities used for LCLS-II, displacement becomes a significant issue as 0.1 mm movement can lead to fundamental mode frequency shifts on the order of 1 kHz/um

Definition

- Lorentz Force Detuning
  - RF Gradient
- Microphonics
  - Pressure Fluctuations
    - Cryogenics
  - Mechanical Distortions
    - Cryogenics
    - Vacuum Equipment
    - HVAC
    - Water
    - Unknown Unknowns (Larry)
  - Cable variations

Lorentz Force Detuning

- Dynamic vs Static; Pulsed vs CW

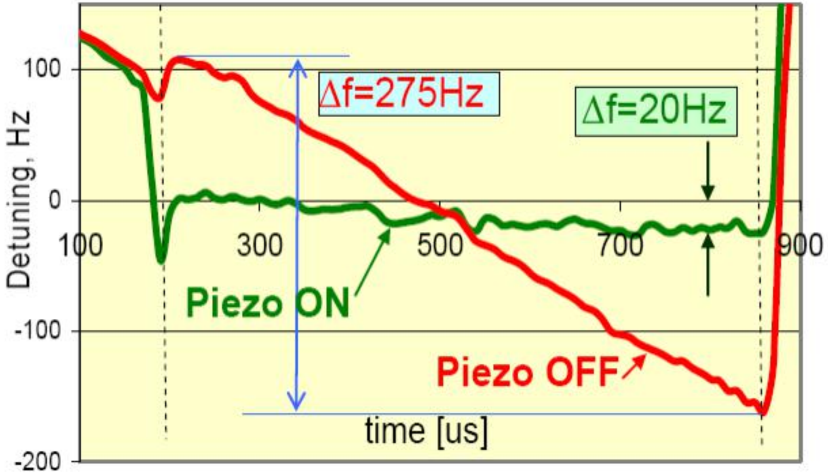


Figure 7: CCII average Lorentz force detuning at EAcc=26MV/m with and without compensation

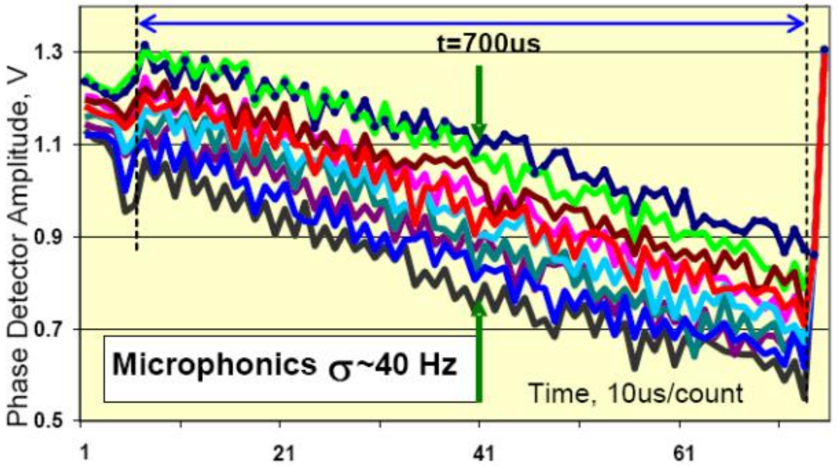


Figure 9: Pulse-to-pulse variations in the CCII phase detector signal due to microphonics.

FIRST FERMILAB RESULTS OF SRF CAVITY LORENTZ FORCE DETUNING COMPENSATION USING A PIEZO TUNER. Proceedings of SRF2007, Peking Univ., Beijing, China. http://accelconf.web.cern.ch/AccelConf/srf2007/PAPERS/TUP57.pdf

The Math

- The steady state amplitude and phase controls needed for microphonics is given by:

$$P_{RF} = \frac{(\beta+1)L}{4\beta Q_{FPC}(r/Q)}\left\{(E + I_0 Q_{FPC}(r/Q)cos\varphi_B)^2 + \left(2Q_L\frac{\delta f}{f_0}E + I_0 Q_{FPC}(r/Q)sin\varphi_B\right)^2\right\}$$

$$\varphi_{RF} = arcTan\left(\frac{2Q_L\frac{\delta f}{f_0}E + I_0 Q_{FPC}(r/Q)sin\varphi_B}{E + I_0 Q_{FPC}(r/Q)cos\varphi_B}\right)$$

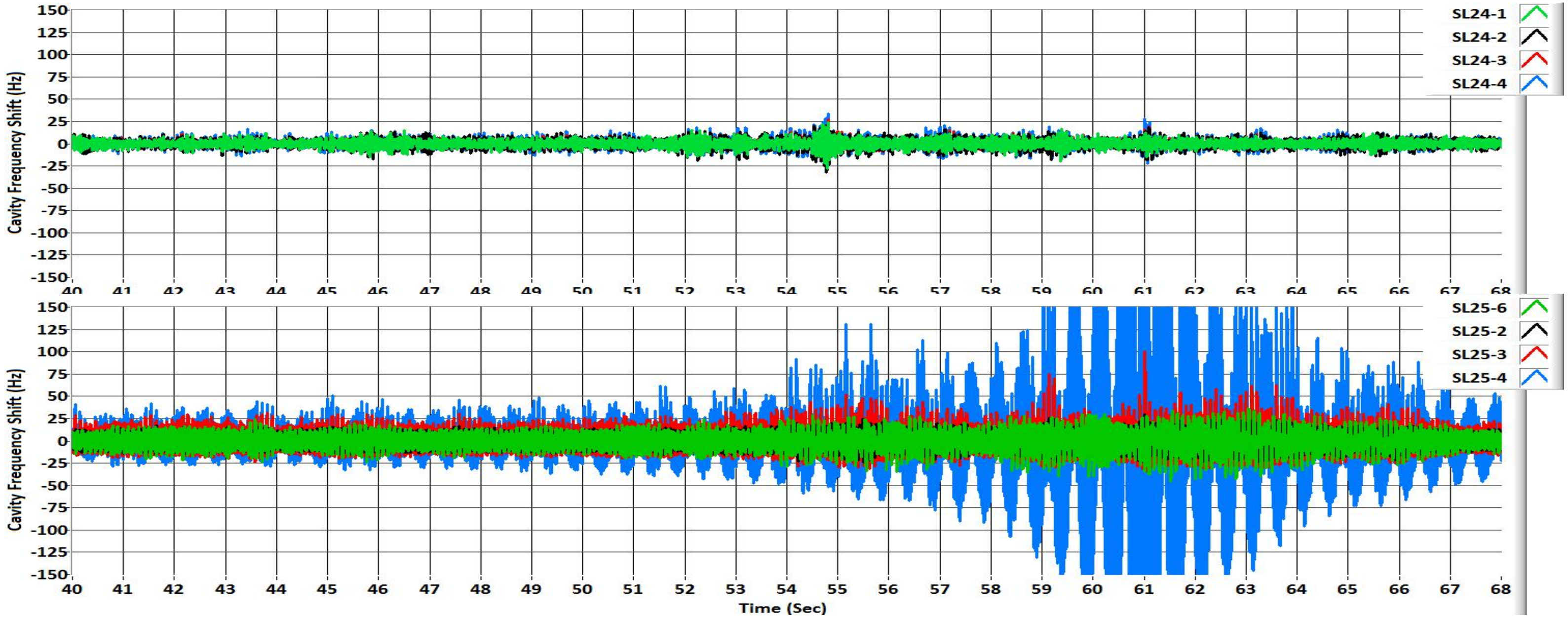
- **One interesting outcome of the math is that beam loading reduces the control requirements due to microphonics.**

***Frequently folks use the loaded-Q, Q_L in place of the fundamental power coupler-Q, Q_{FPC}.**

Other Labs

- US Labs have started holding Microphonics Workshops, with the first held in 2015
  - https://indico.fnal.gov/event/10555/
- Microphonics is not a single-lab problem

Comparison of a Hardened (SL24) and Zone With No Improvements (SL25) During Truck Drive By

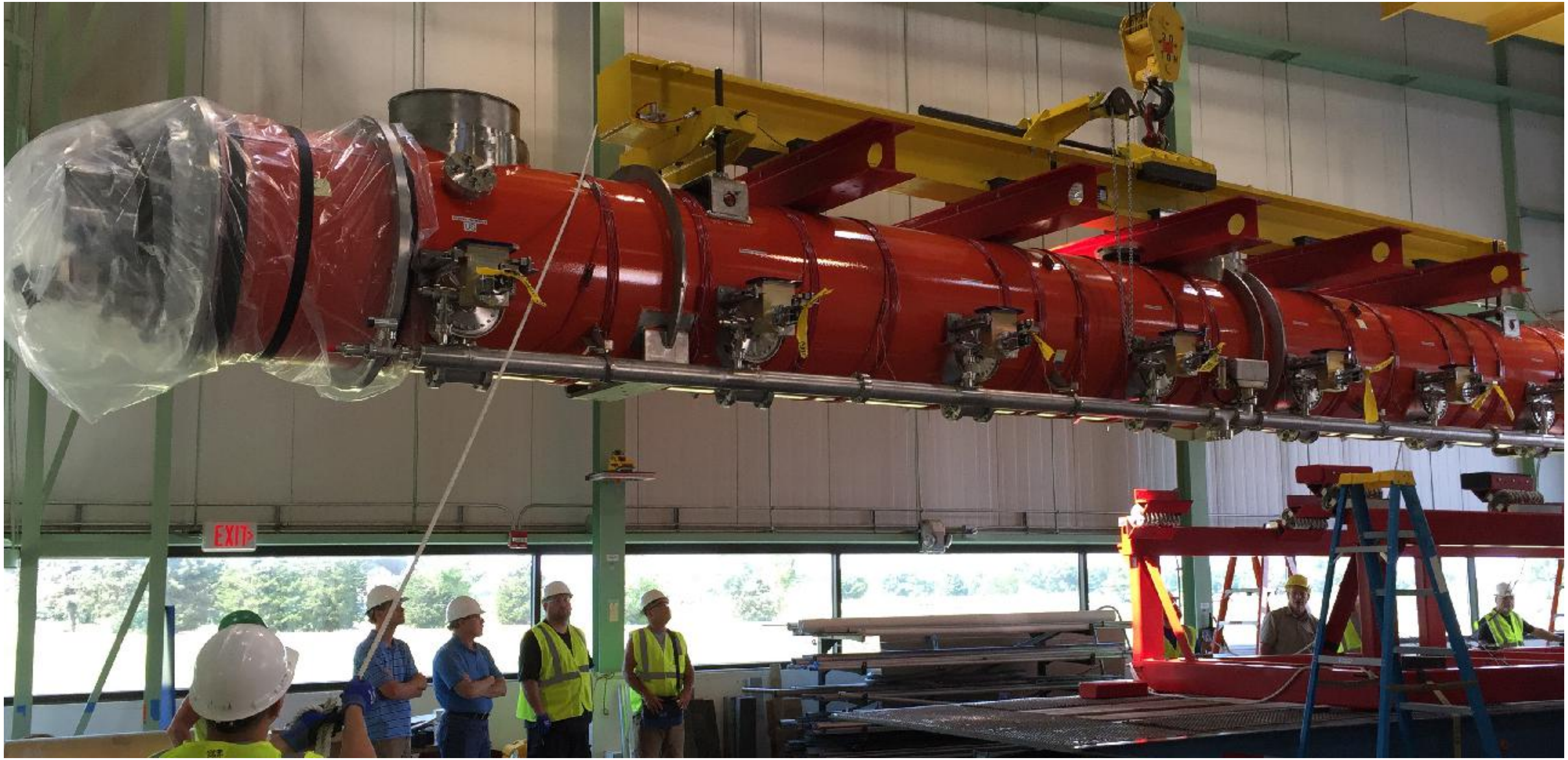


- **A liquid nitrogen truck drove down the south linac service road at about 15 mph passing the zone at time equals about 60 seconds.**
- **Cavities operated in GDR mode at 3 MV/m in order to avoid trips.**

Fermilab

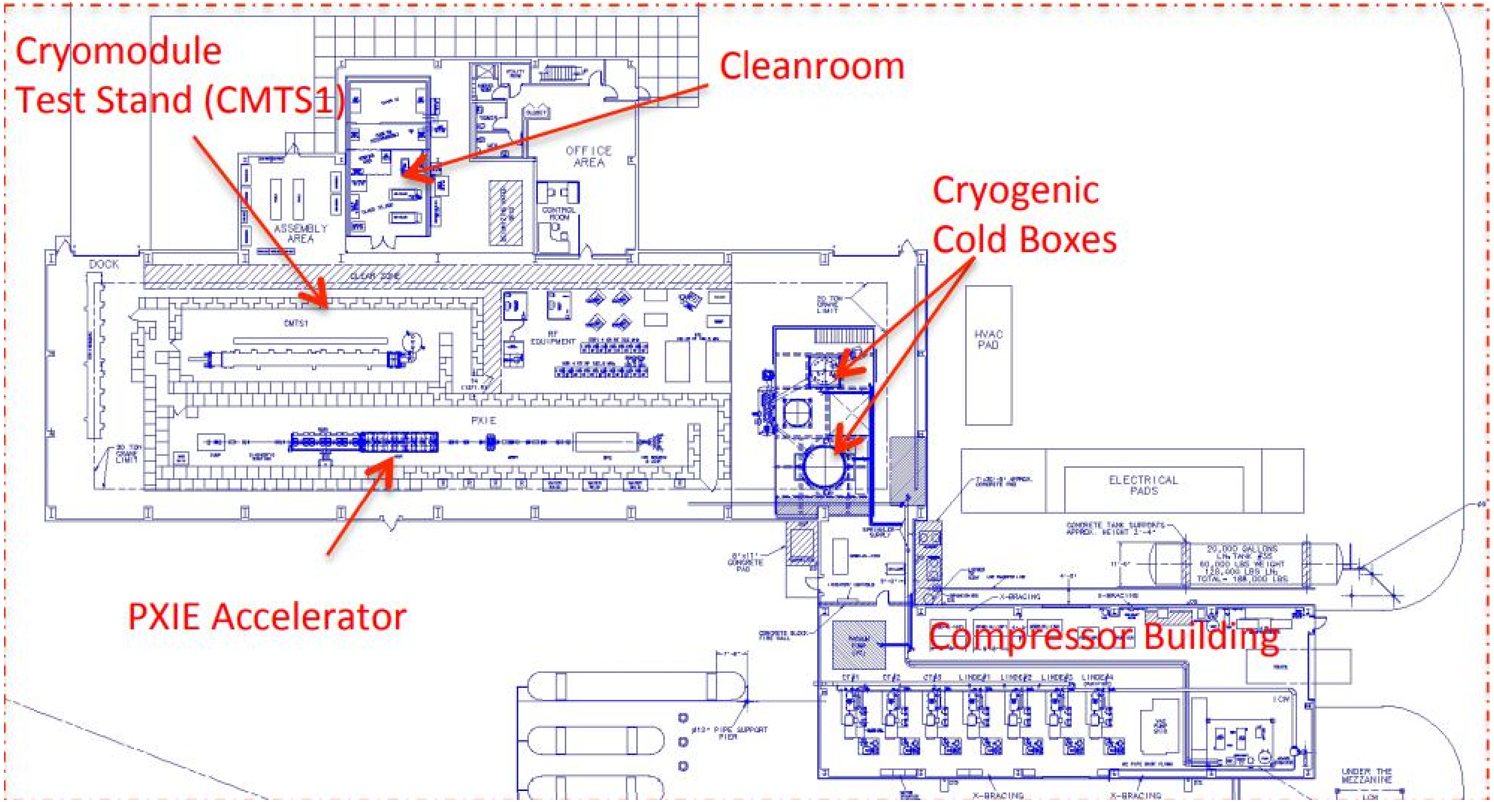
Powers, T. *Microphonics and Energy Jitter.* August 2017.

Fermilab CMTF



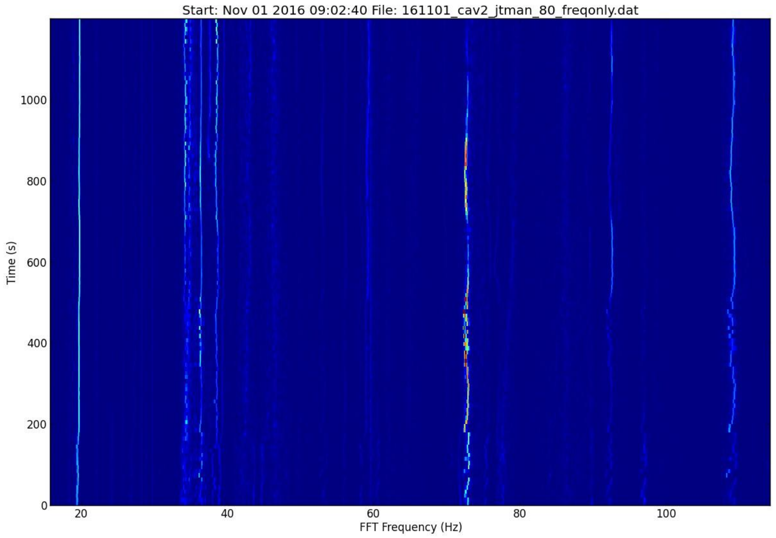
Leibfritz, Jerry. CMTF Infrastructure.
https://indico.fnal.gov/event/9404/session/3/material/slides/1?contribId=14

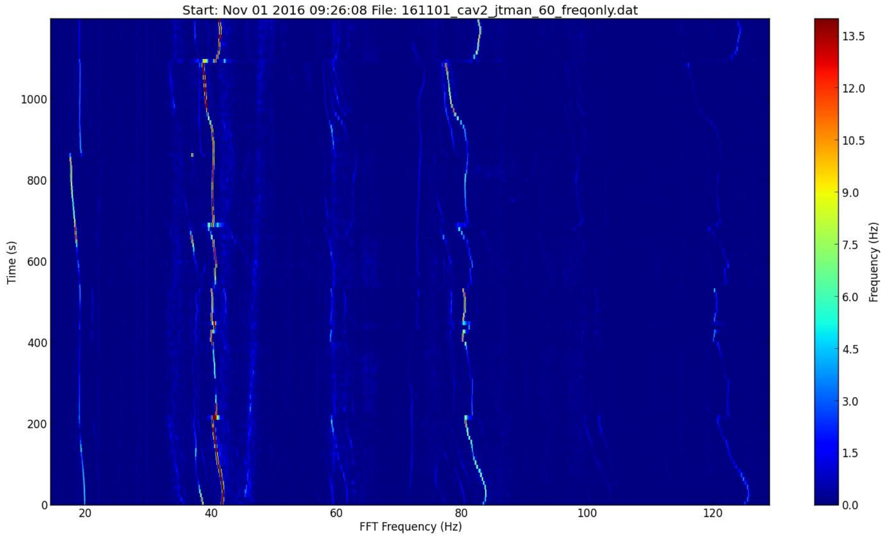
Fermilab CMTF



Leibfritz, Jerry. CMTF Infrastructure.
https://indico.fnal.gov/event/9404/session/3/material/slides/1?contribId=14

Initial Findings – F1.3-01

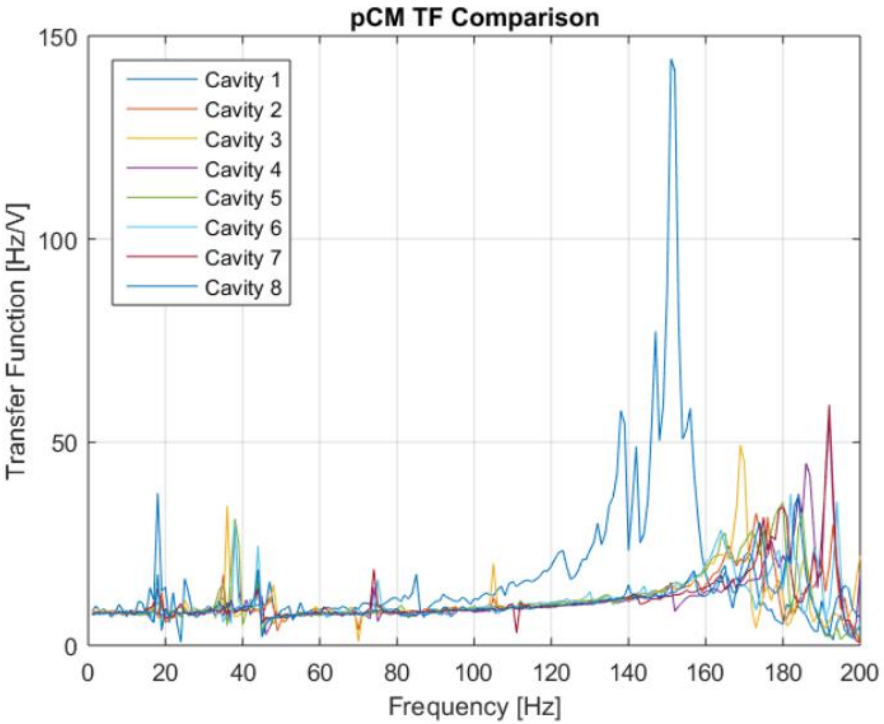


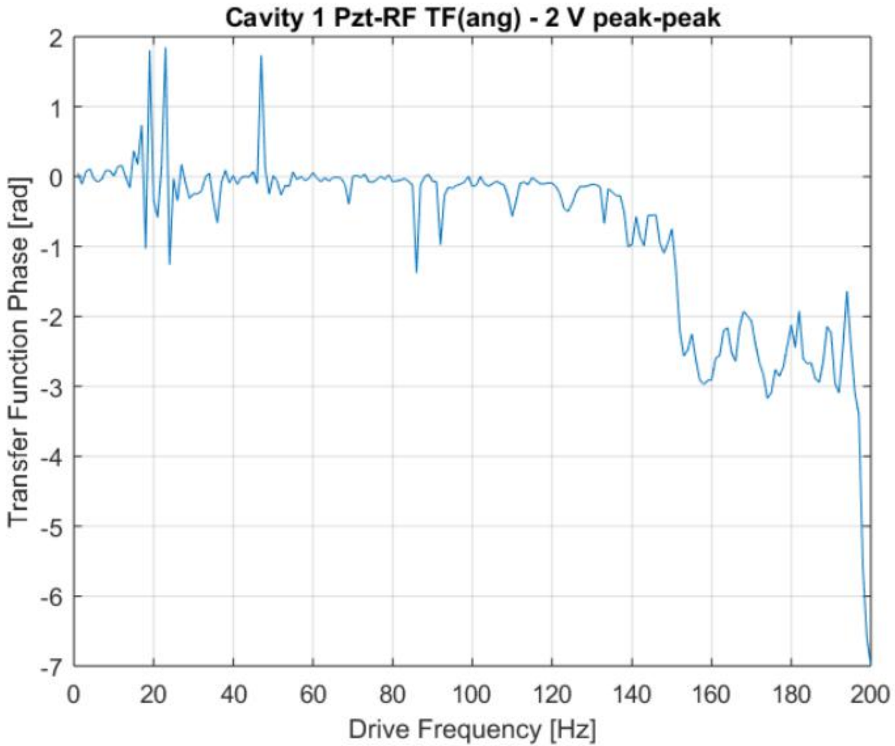


JT Valve at 60% open

JT Valve at 80% open

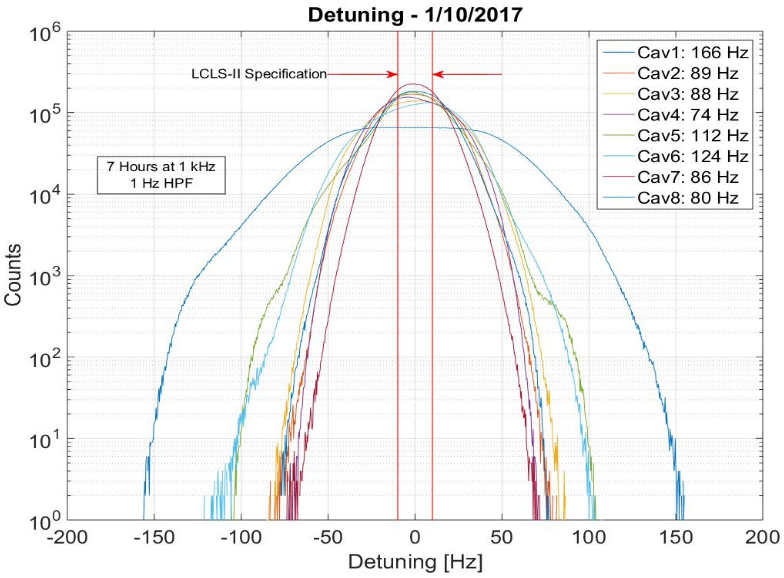
Transfer Functions

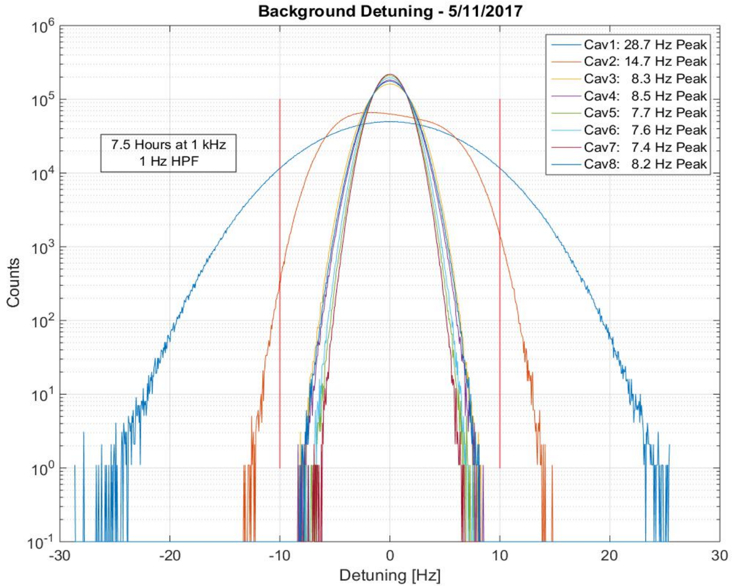




As–cooled vs Post–Improvement

- Comparing performance of the standard cryogenics configuration, the microphonics environment in the F1.3–02 is a factor of ~10 improved
- Significant improvements in stability of the system, leading to a far more predictable detuning environment





Sources and Possibilities

- Injection method
  - The two-phase pipe was modified to include a baffle to avoid wind any damming effects or wind dragging due to the injection
- Cryomodule tilt due to tunnel installation
  - Teststands include a tilt to mimic actual installation. Theories on gas and liquid Helium flow abound
- Cool-down line and piping
  - Dead-head on cool-down line with osciallations in attached temperature sensors. Secondary effect, or primary problem?
- External sources
  - Vacuum pumps? Facility water? Waveguide transmission?
- TAOs
  - Rott developed theory in 1969 (see TAO part 1)
  - Requires careful design of system

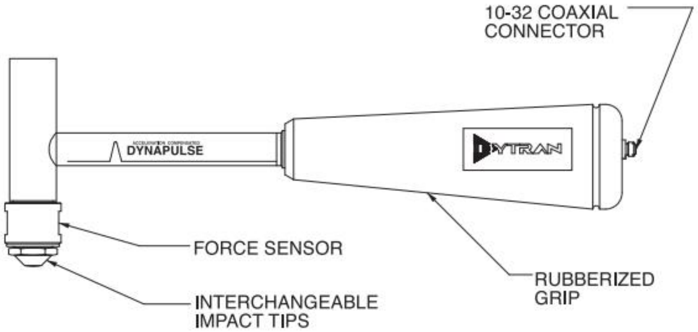
Determination

- Considerations of the type of noise sources is necessary. Narrow-band vs broadband have different algorithms for efficient cancellation
- Stability analysis
  - Understanding of system frequency-domain response over time and bandwidth of signals
  - Cross-correlation analysis and spectral density analysis with windowing can provide further details
  - Plotting statistical variance

A Closer Look

Impulse Testing

- Broadband, calibrated source
- Simultaneous capture with sensors
- Modal Testing on warm structures
- Cavity–to–cavity coupling is readily tested



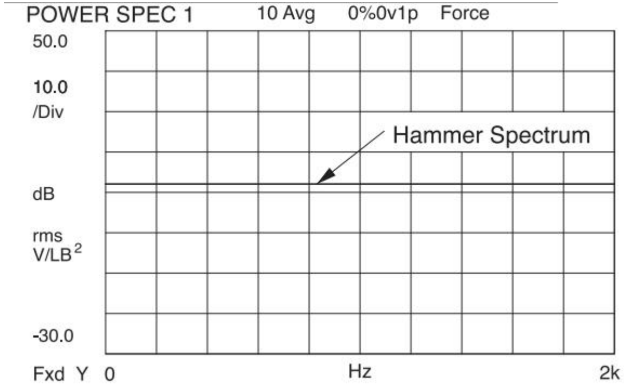


Figure 2: Impulse Spectrum, Aluminum Tip, No Extender

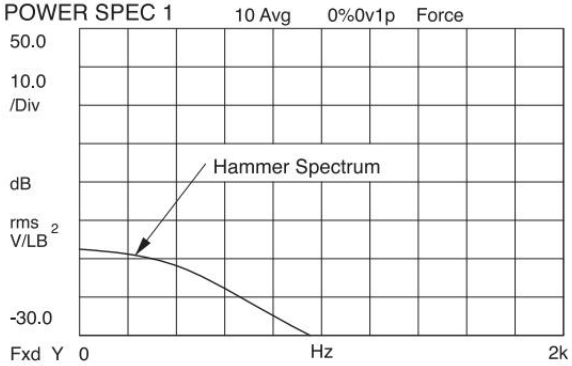
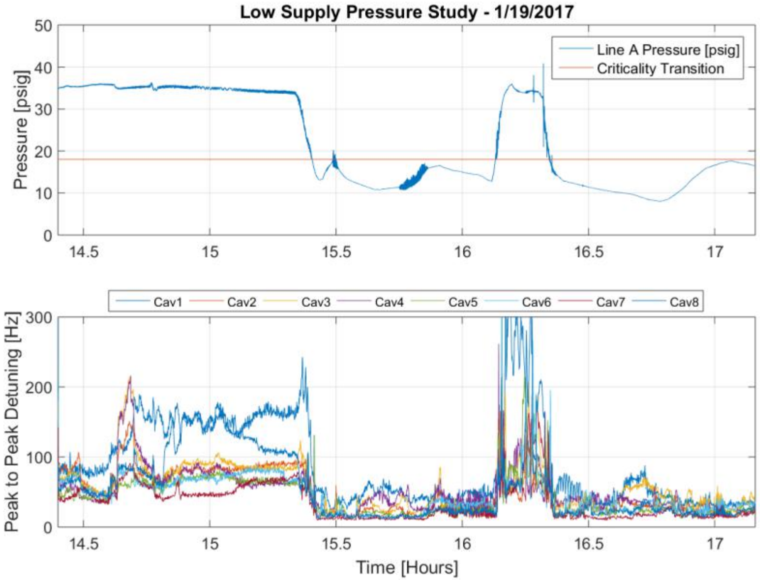


Figure 4: Impulse Spectrum, Soft Plastic Tip, One Head Extender

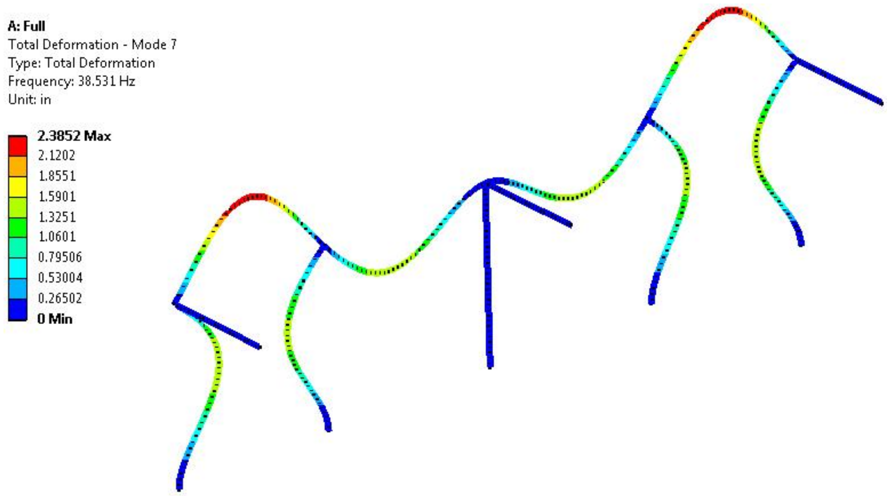
Introduction To Impulse Hammers,
http://www.dytran.com/assets/PDF/Introduction%20to%20Impulse%20Hammers.pdf

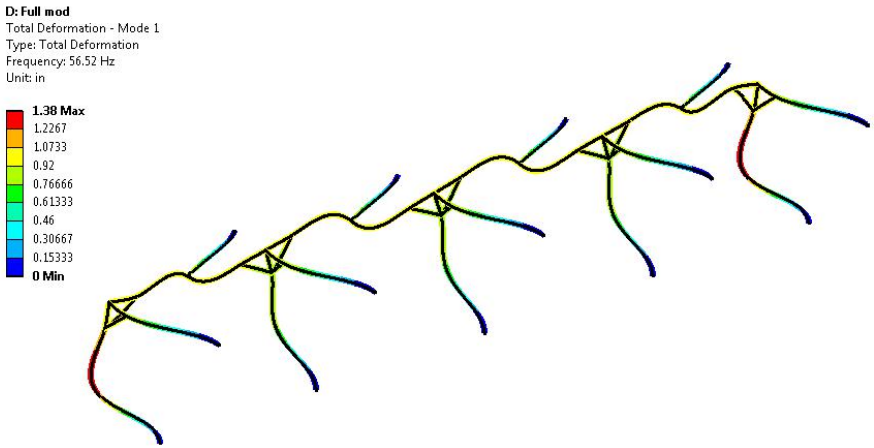
Microphonics vs Cryogenic System Studies

- Initially is was unknown that TAOs were the culprit
- Several cryogenic variables were varied during long data captures to find correlations.
- Discovered that at Subcritical Supply Pressures the microphonics improved by **factor of 10 !**
- In addition: reduction in steady-state flow rate from 4.7 g/s to 1.75 g/s, supply pressure stabilized, valve ice melted
- This coincident combination of improvements suggests TAOs in the valves were the main contributor to the high microphonics levels and 2K Static Heat Load



Mechanical Modes





Mode No.	Freq (Hz)
1.	8.5949
2.	8.9183
3.	11.622
4.	29.559
5.	33.823

Mode No.	Freq (Hz)
1.	56.52
2.	57.769
3.	57.81
4.	57.829
5.	58.226

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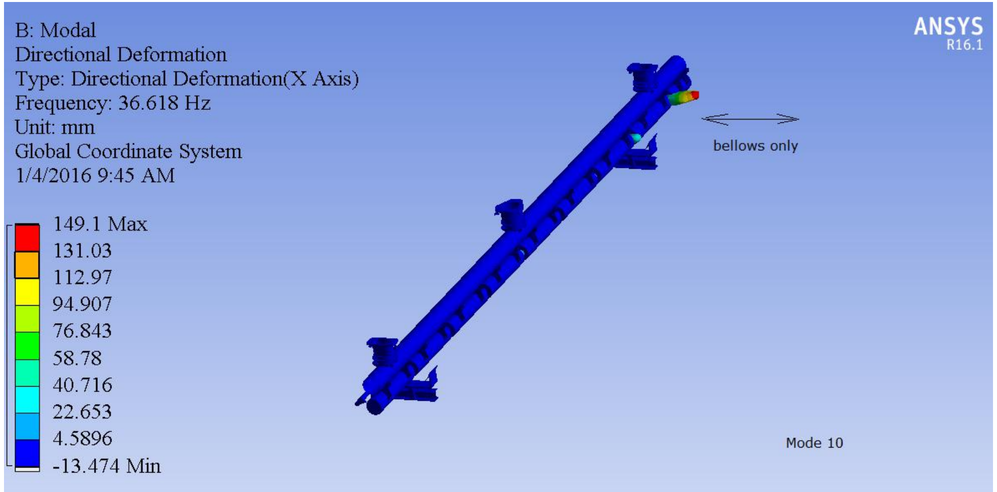
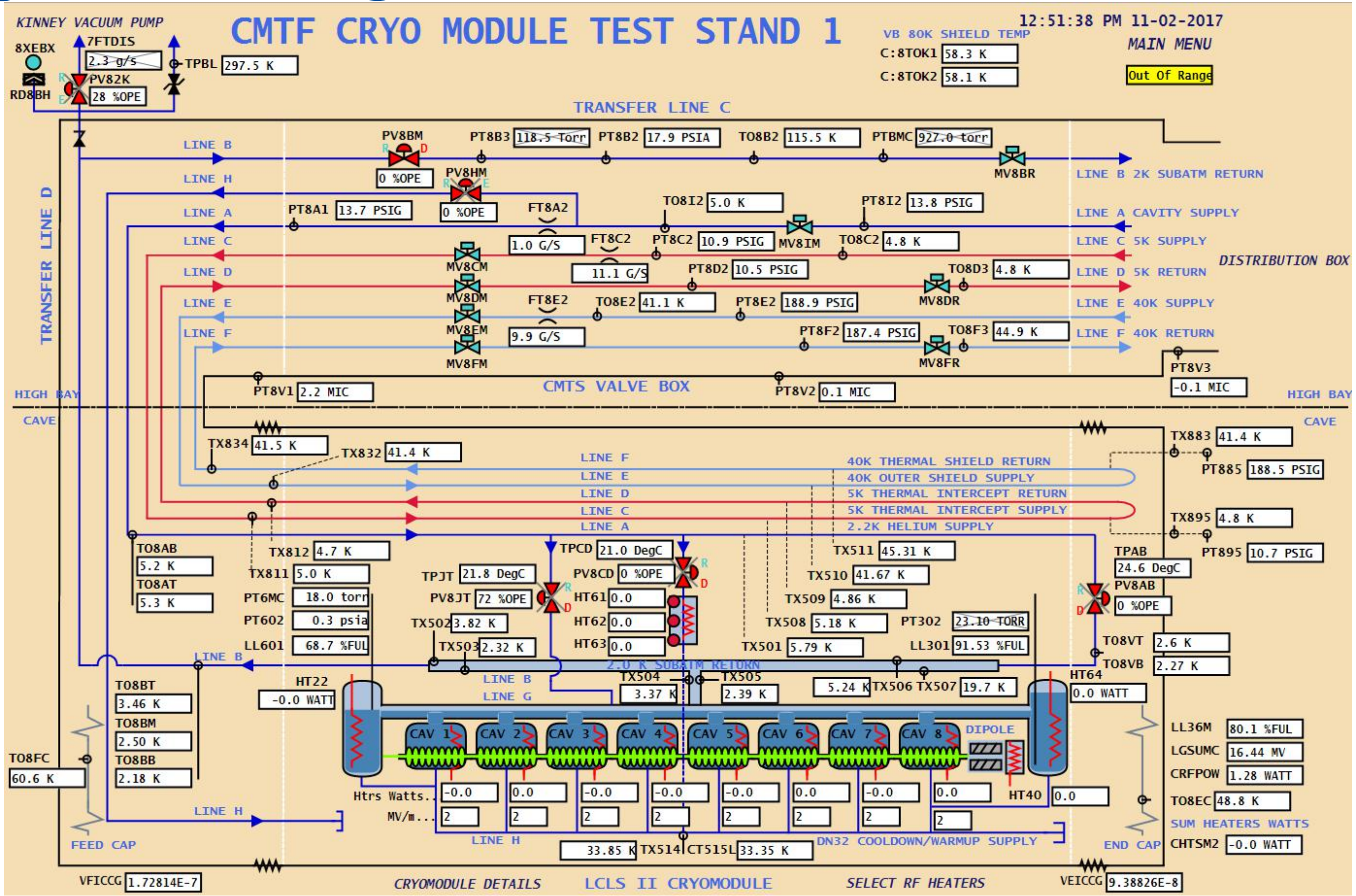
Mechanical Modes



Mode	Frequency (Hz)
1	7.5612
2	17.759
3	20.540
4	22.055
5	25.182
6	26.733
7	27.641
8	31.911
9	33.422
10	36.618

Facility Monitoring



Diagnosis

- Fast pressure sensors
- Long-term data captures; Note FFT resolution
- RF power measurements
- Bubbles
- Cell Phones
- Microphones
- Geophones

Mitigation

- What is active compensation？
  - Is passive compensation and good design a form of active compensation？

Algorithms

- Least Mean Square (LMS)
- Kalman Filtering
- ‘Analog’ Filter Bank
- Direct feedback
- Anything else？
- Active Cancellation
- Pulse-to-pulse correction

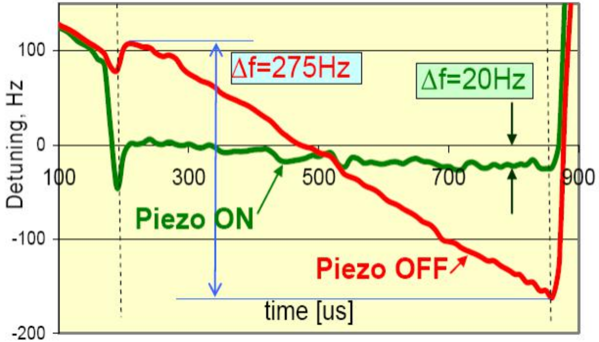


Figure 7: CCII average Lorentz force detuning at EAcc=26MV/m with and without compensation

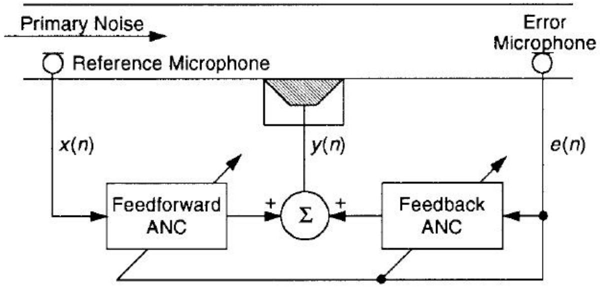
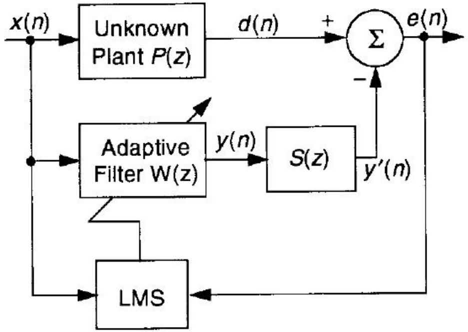


Fig. 17. Hybrid ANC system with combination of feedback ANC and feedforward ANC.



;. 3. Simplified block diagram of ANC system.

Kuo, S and Morgan, D.. *Active Noise Control: A Tutorial Review*. PROCEEDINGS OF THE IEEE, VOL. 87, NO. 6, JUNE 1999. pp 943-973.

Mitigation

- LMS, NXLMS, FNLMS
  - Definition of basis function very important
  - Some functions have feedback inherent in the structure
- Model-based controllers
  - Currently available anywhere?
  - A model is necessary regardless of whether this is dynamic to have a base design to compare to
- Full simulation of mechanical design
  - Tuner, piping and support equipment can all contriubte to expected microphonics and LFD
- A mix of narrowband and broadband suppression techniques are likely desired, with characterization of all sources a necessity.

Detuning Filter Bank – Feed Forward Controller

- Discrete-time State Space Realization
- General form for a system whose
  - Outputs and internal states depend linearly on the inputs and internal states
- u is the detuning
- y is the piezo drive signal
- x are estimates of the amplitudes of the cavity mechanical modes
- **A** can be decomposed into a 2x2 block diagonal matrix
  - Ideal for implementation in an FPGA firmware

$$x_{k+1} = \mathbf{A} \quad x_k + \mathbf{B} \quad u_k$$
$$y_{k+1} = \mathbf{C} \quad x_{k+1} + \mathbf{D} \quad u_k$$

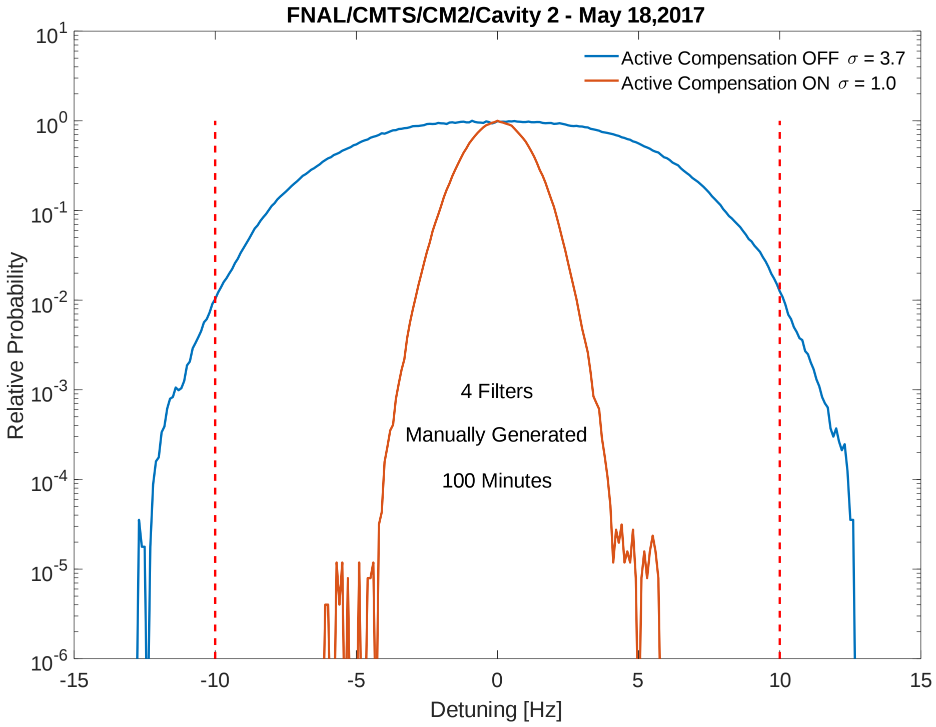
$$\mathbf{A}^{(j)} = \begin{bmatrix} e^{-\frac{\Delta t}{\tau_j}} \cos \omega_j \Delta t & e^{-\frac{\Delta t}{\tau_j}} \sin \omega_j \Delta t \\ -e^{-\frac{\Delta t}{\tau_j}} \sin \omega_j \Delta t & e^{-\frac{\Delta t}{\tau_j}} \cos \omega_j \Delta t \end{bmatrix}$$

$$\mathbf{B}^{(j)} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$\mathbf{C}^{(j)} = \begin{bmatrix} G^{(j)} \cos \varphi^{(j)} & G^{(j)} \sin \varphi^{(j)} \end{bmatrix}$$

Manual Compensation in CM2/Cavity 2

- Detuning fed to a bank of parallel 2nd order IIR filters
  - Sum of filter outputs drives piezo
- Filter coefficients (frequency, bandwidth, gain, phase) are programmable
- Manually tuned filter coefficients can suppress cavity detuning by a factor of 3 or more



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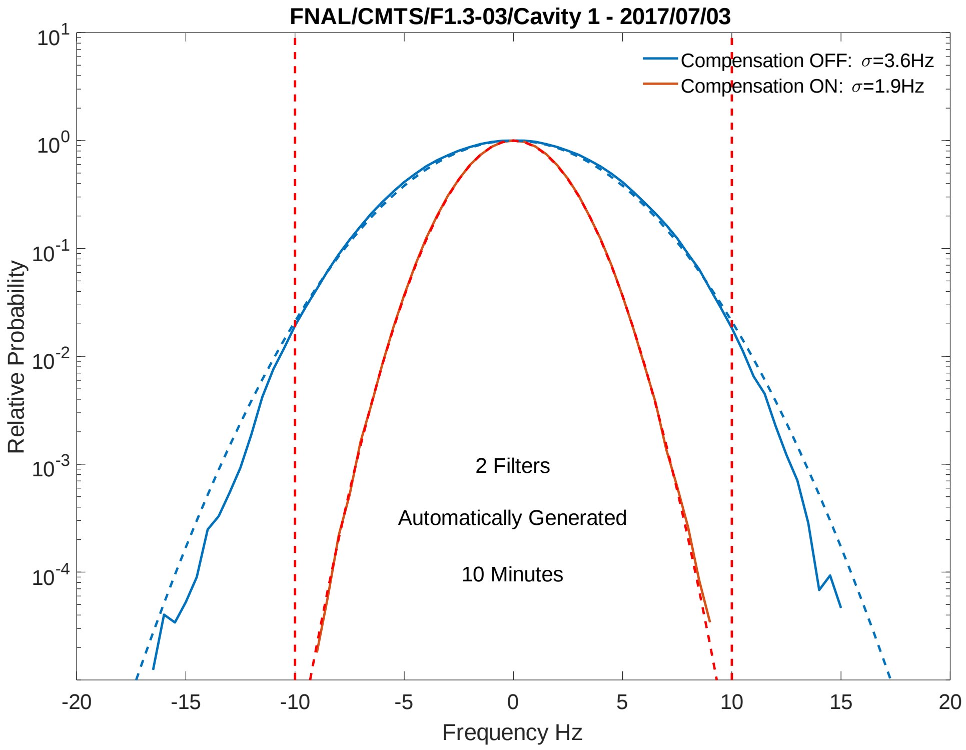
Automatic Compensation in CM3/Cavity 1

- Automated algorithm uses Least Squares to determine filter coefficients from
  - measured detuning noise spectrum and
  - piezo/detuning transfer function
- Single overall gain adjusted manually



BESSY Testing

- Feedback: 1–2 Hz 3 dB low-pass cutoff PI controller, Kp ~ 10–20, limited by tuner resolution and peak event stability
- Feedforward: Adaptive fourier-domain LMS
  - Deconvolves piezo transfer function from the measured microphonics
  - Phase shifter to compensate for loop phase
  - Generated based on IFFT of detuning error signal FFT deconvolved form transfer function

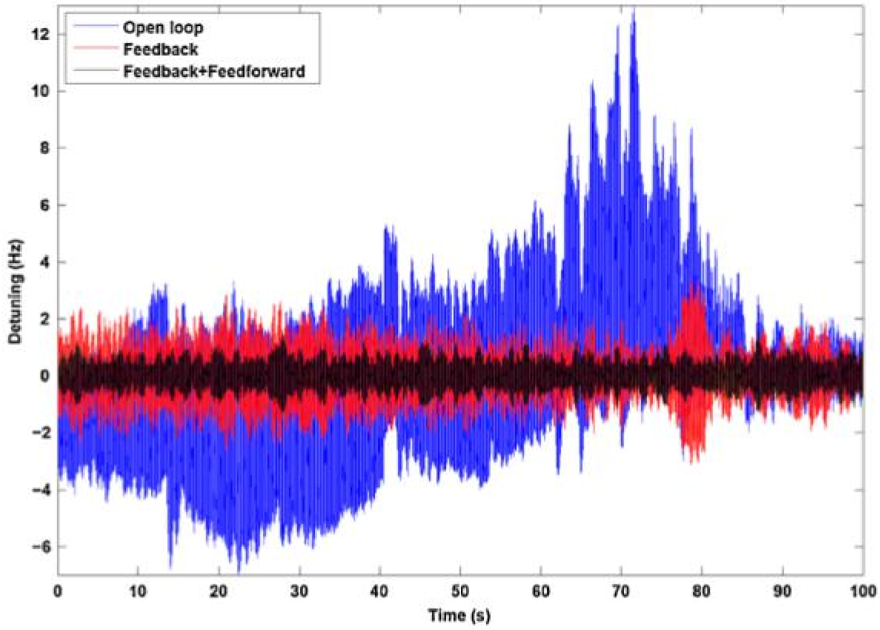
$$y_n = \vec{w}_n^T IFFT(\hat{\vec{e}}_n / H_{\text{piezo}\to\Delta f})$$

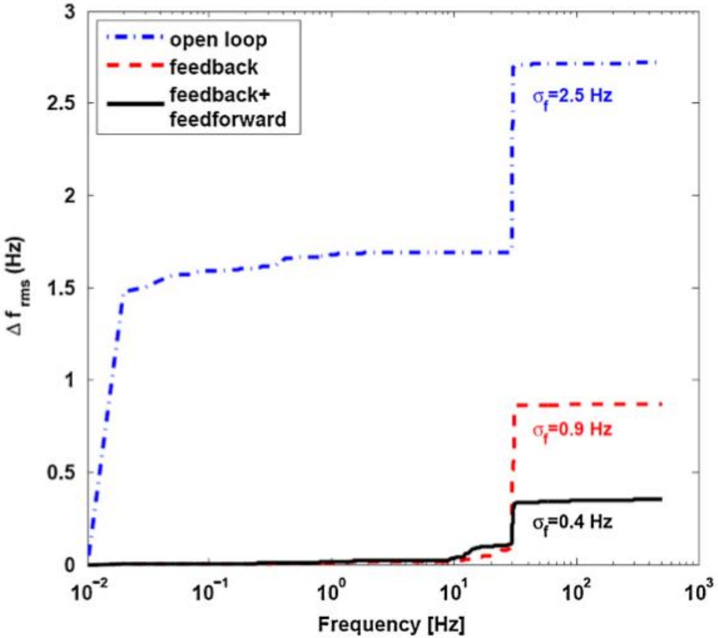
$$e_n = H_{\text{ext}\to\Delta f} z_n - H_{\text{piezo}\to\Delta f} y_n \sin(\phi_{\text{shift}}).$$

$$\vec{w}_{n+1} = \vec{w}_n - \mu \frac{e_n \vec{x}_n}{\beta + \vec{x}_n^T \vec{x}_n}$$

Neumann, A., et al. *Analysis and active compensation of microphonics in continuous wave narrow-bandwidth superconducting cavities.* PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 13, 082001 (2010)

BESSY Testing





- LMS with Low–Frequency PI feedback

Neumann, A., et al. *Analysis and active compensation of microphonics in continuous wave narrow-bandwidth superconducting cavities.* PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 13, 082001 (2010)

- LMS with N notches per cavity
- Pipelined architecture

$$H_{\mathrm{ANC}}(z) = \sum_{i=1}^{n_\omega} \mu_i A_{p,i}^2 \left[\frac{z\cos(\omega_i - \phi_{p,i}) - \cos\phi_{p,i}}{z^2 - 2z\cos\omega_i + 1} \right]$$

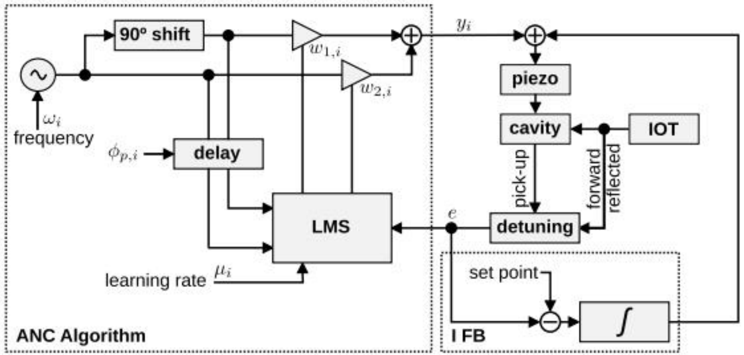
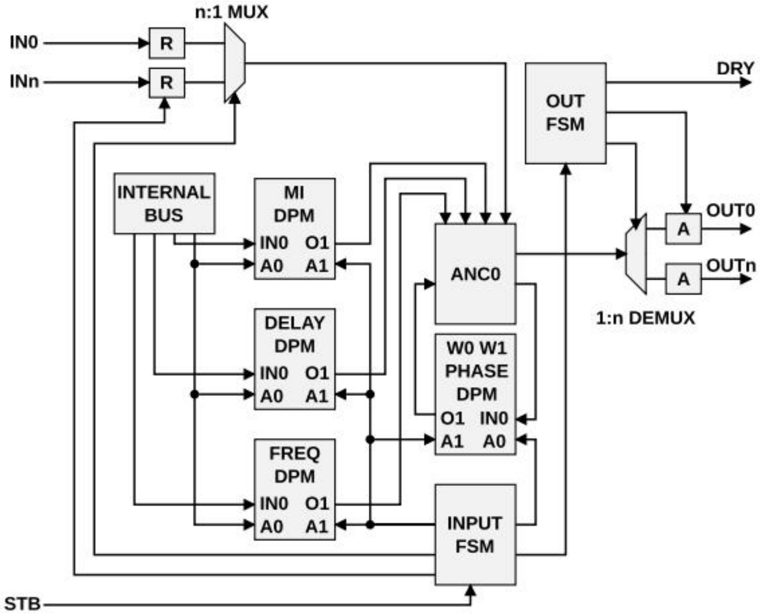
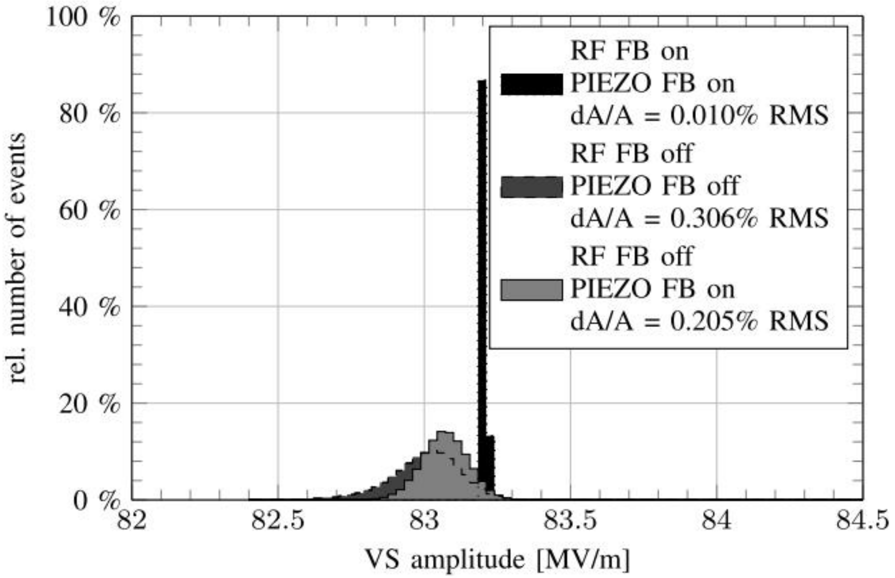


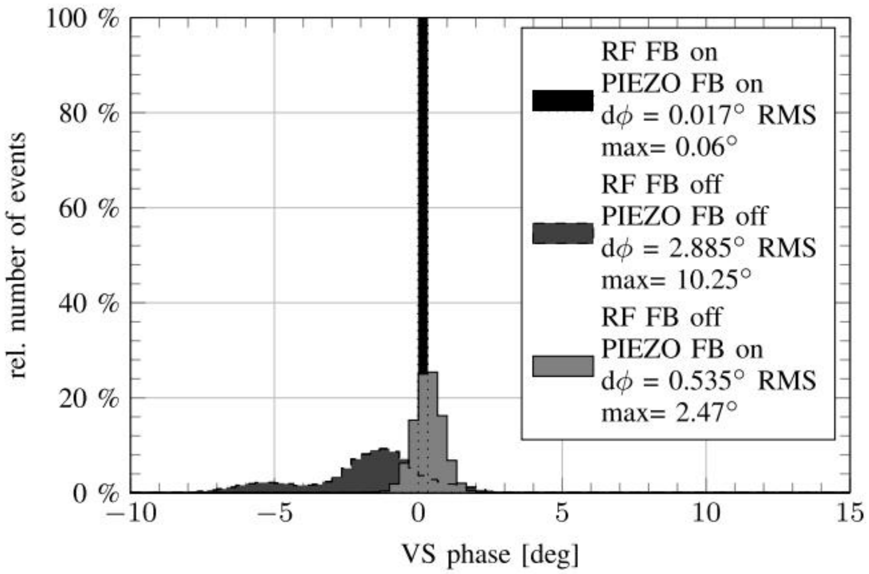
Fig. 6. Detuning compensation algorithm scheme.



Rybaniec, R., et al. *FPGA-Based RF and Piezocontrollers for SRF Cavities in CW Mode.*
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 6, JUNE 2017

DESY





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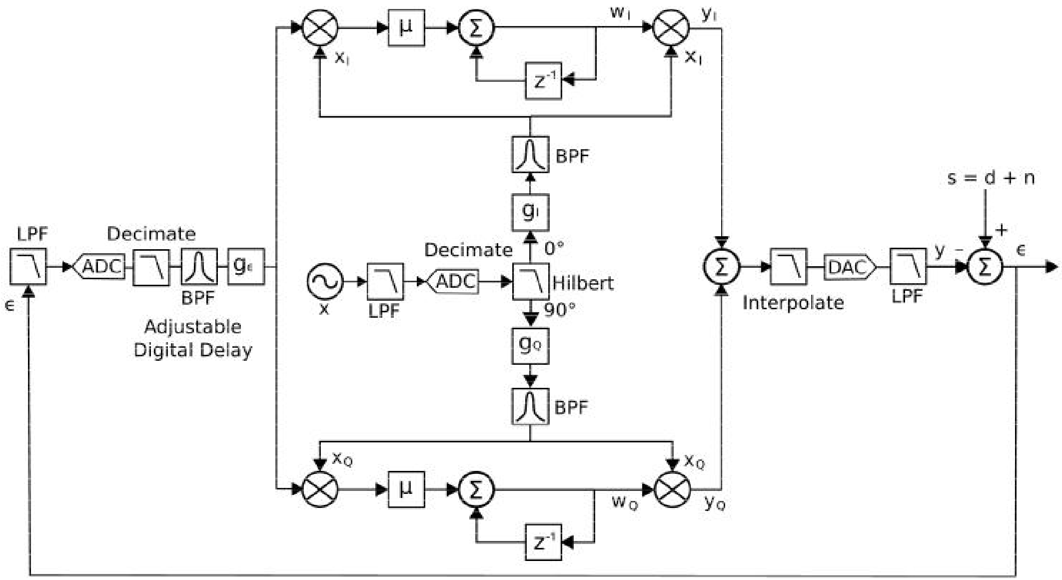
Rybaniec, R., et al. *FPGA-Based RF and Piezocontrollers for SRF Cavities in CW Mode.*
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 6, JUNE 2017

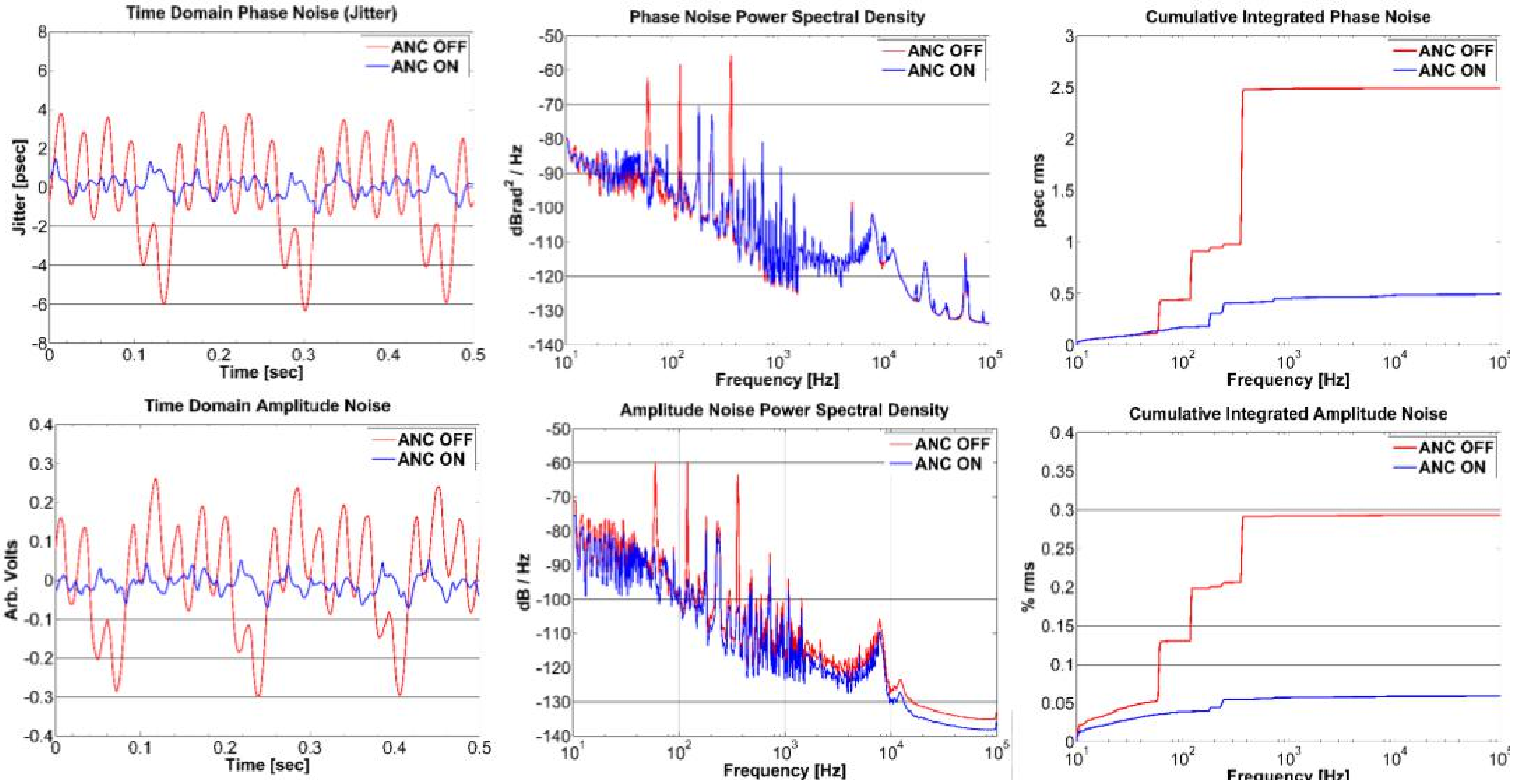
APS

- Narrowband $(400$th order$)$ adaptive notch filter
- Excellent for removing discrete, narrowband sources



Berenec, T., et al. *General Narrowband Noise Cancellation Development at the APS.*
First Microphonics Workshop. https://indico.fnal.gov/event/10555/

APS



Berenec, T., et al. *General Narrowband Noise Cancellation Development at the APS.* First Microphonics Workshop. https://indico.fnal.gov/event/10555/

Conclusion

- Mitigation and control techniques requires an understanding of systematic issues
  - Working in a black box is not a good idea
  - Don't work on it alone and never take anything for granted
- Controller stability analysis is a necessity

- Thank You

Additional Slides

Audio Interpretations

- Look at things in different ways

TO REVIEW

- Contgrol bandwidth and theory
- DC Robinson Stability (neumann 2015)
- Warren microphonics and ARC. Download and use
- LCR circuit model used for feedback (neumann [11])
- Get audio recordings from emails and save. LCLS-II pCM
- get echo cancellation paper in correct location
- Model-based control
- LFD field**2 proportion for detuning vs integrator (square of cavity gradient. Makes sense, as we're balancing power)
- Standard feedback on the signal with notches helps. Is this good enough? That is the real question. Pull from wepty036

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